Time dependent behaviour of fluids filled geomaterials: application to reservoir formations

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Abstract # 202

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ABSTRACT

In this paper a rate dependent model for geomaterials saturated by a mixture of immiscible fluids is presented. The proposed constitutive law generalizes the isotach approach to the elastoplastic strain hardening based constitutive laws for partially saturated soils. The formulation encompasses rate and creep effects together with suction dependency on creep. Some perspectives about the constitutive modelling of time-dependent behaviour of geomaterials saturated by a single or two fluids, including soft rocks are proposed. Practical applications include modelling of underground carries submitted to humidity changes, oil reservoir formations or geological storage of CO_2. In this study, the model formulation is presented and numerical predictions are compared with available experimental results on oil reservoir chalk.

INTRODUCTION

Time dependency of the behaviour of geomaterials has been experimentally recognized for a large variety of materials, including clays [1], sands, rockfill [2], rocks and soft rocks [3, 4, 5] and concrete. Time effects involve distinct aspects of deformational processes. Concerning the irreversible deformations, creep phenomena are generally observed under constant loads. A dependence of the strength on the rate of applied load or strain is also experimentally observed. Experimental creep curves show a proportionality of the strains to the logarithm of time, the proportionality coefficient being the secondary compression index C_α or λ^t, often used in engineering practice.

Despite a significant practical interest, only few studies have focused on the influence of suction on time effects. Recent studies on rockfill material have been presented in [2] and on reservoir chalk in [4, 5].

This paper briefly presents observed influence of suction level or fluid nature on the time dependency of the behaviour. A constitutive model is then proposed in the

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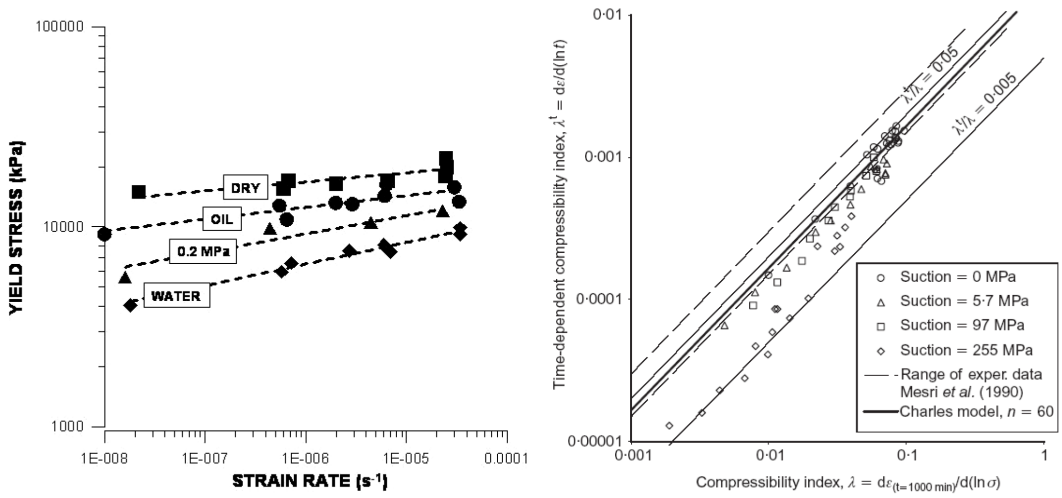

(a) (b)

Figure 1. (a) Variation of yield stress of chalk with strain rate during CRS oedometric tests, 0.2 MPa refers to oil-water suction [5]. (b) Parameter λ^t/λ for saturated and partially saturated rockfill [2].

framework of strain hardening elastoplasticity and isotach approach. Numerical simulations illustrating the capabilities of the model and its validation on the basis of available experimental data are finally proposed. It is worth noting that, in this paper, the terminology “partially saturated” is preferred to the classical “unsaturated” term as representative of a physical state where two immiscible fluids interact in the porous space. If one of the fluids is air, the soil is unsaturated.

EXPERIMENTAL OBSERVATIONS

It is generally accepted that the elastic limit is related to the strain rate at which the material is loaded [6]:

$$\sigma_y = A + \alpha \log \dot{\varepsilon} \tag{1}$$

where A and α are material parameters. Figure 1 suggests that suction affects the time dependent behaviour of chalk and rockfill. It will thus be supposed that parameters A and α are suction dependent in the model formulation presented hereafter. This last point is the key feature of the rate dependent mechanical behaviour of partially saturated materials. The purpose of this paper is to include these coupled aspects within an elastoplastic framework to model the mechanical behaviour of partially saturated geomaterials, taking into account rate effects.

It is worth noting that the nature of the fluid (water, air or oil) saturating the porous volumes plays a significant role in terms of strength (see Figure 1 (a)). Concerning elastic deformation, some evidences show an influence of strain or stress rate on the apparent stiffness of some materials (see the initial slopes of experimental curves of Figure 4). These effects will however not be taken into account in this study.

MODEL FORMULATION

The elastoplastic model presented here, called RASTRA, is a rate dependent model developed adopting the isotach approach proposed by Šuklje [3] and Bjerrum [1] within the framework of hardening plasticity. It also includes effects of partial saturation both on the time dependency itself and on the mechanical behaviour. These features have been developed on the basis of the well-known Cam-clay model for saturated soils and particularly its extension to unsaturated states proposed by Alonso and his co-workers [7]: the Barcelona Basic Model (BBM). For the sake of conciseness, BBM will not be presented in detail here.

As in [7], net stress ($\overline{p} = p - u_a$) and suction ($s = u_a - u_w$) have been considered as stress state variables. In this paper, it is assumed that time effects do not influence the elastic behaviour of the material. Thus the elastic law of BBM is adopted:

$$\mathrm{d}\varepsilon_v^e = \frac{\kappa}{v}\frac{\mathrm{d}\overline{p}}{\overline{p}} + \frac{\kappa_s}{v}\frac{\mathrm{d}s}{(s + p_{atm})} \tag{2}$$

Concerning the plastic behaviour of unsaturated soils, the key feature of BBM is the introduction of a suction hardening within the definition of the preconsolidation pressure, which defines the elastic limit under isotropic conditions, $p_0 = p_0(\varepsilon_v^p, s)$. The proposition made in this paper extends this model to include rate effects by assuming that the preconsolidation stress also depends on the strain rate $\dot{\varepsilon}_v$, $p_0 = p_0(\varepsilon_v^p, s, \dot{\varepsilon}_v)$. Considering expression (1), extension of BBM to include rate effects is introduced in the following way:

$$p_0(\varepsilon_v^p, s, \dot{\varepsilon}) = p_c\left(\frac{p_o^*(\varepsilon_v^p, \dot{\varepsilon}_v)}{p_c}\right)^{(\lambda(0)-\kappa)/(\lambda(s)-\kappa)} \tag{3}$$

$$p_o^*(\varepsilon_v^p, \dot{\varepsilon}_v) = p_{r0}(\dot{\varepsilon}_v)\exp\left(\frac{v}{\lambda(0)-\kappa}\varepsilon_v^p\right) \quad ; \quad p_{r0}(\dot{\varepsilon}_v) = p_{r0}^{ref}\left(\frac{\dot{\varepsilon}_v}{\dot{\varepsilon}_v^{ref}}\right)^{\alpha} \tag{4}$$

In order to introduce suction influence on creep and rate effects on the strength of partially saturated materials, α is assumed to depend on suction. This dependence will be supposed to be linear in a first approach:

$$\alpha(s) = \alpha_0 - bs \tag{5}$$

The elastic domain is then closed in triaxial space assuming the same yield function as in BBM:

$$f \equiv q^2 - M^2(\overline{p} + p_s)(p_0 - \overline{p}) = 0 \tag{6}$$

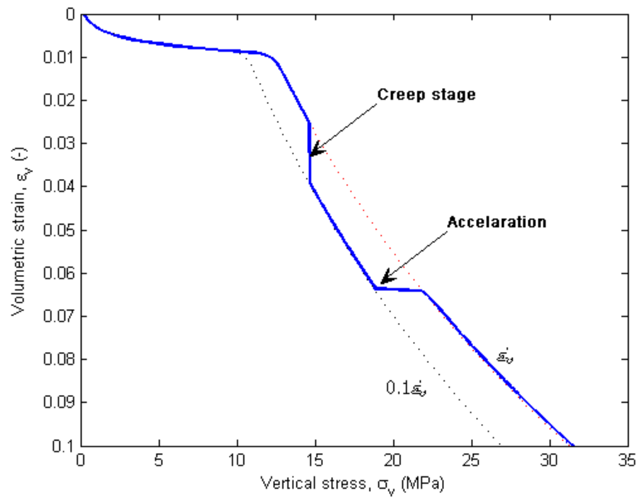

Figure 2: Constant rate of strain (CRS) oedometer test simulations at various strain rates and a constant suction of 2 MPa.

The model is completed by giving the plastic flow rule. As in original BBM, it will be chosen as (α_g being a function of parameters M, $\lambda(0)$ and κ):

$$d\varepsilon_v^p = d\mu\,\alpha_g \frac{\partial f}{\partial p} \quad ; \quad d\varepsilon_s^p = d\mu \frac{\partial f}{\partial q} \tag{7}$$

where $d\mu$ is the plastic multiplier obtained using the consistency condition $df = 0$. Only four parameters related to the modelling of rate effects have been introduced with respect to the original Barcelona Basic model, namely $\dot{\varepsilon}_v^{ref}$, p_{r0}^{ref}, α_0 and b.

MODEL VALIDATION

Numerical simulations using RASTRA model are now presented in order to show the capabilities of the model in terms of coupled modelling of time and partial saturation effects. The model parameters used in the simulations presented in the following figures are summarized in Table 1. Figure 2 illustrates the effects of changes of the strain rate during oedometric loadings at constant rate of strain (CRS tests). The numerical test consists in three compression stages at two distinct strain rates (a fast strain rate corresponding to 10^{-6} s^{-1} and a slow strain rate, 10 times slower). After the first compression, a creep phase is simulated. The latter is numerically performed by simply decreasing the strain rate from the fast rate to the slow rate. It may be observed that the creep phase effectively induces irreversible strains at constant vertical stress and that the acceleration of the strain rate allows the material to undergo higher stresses (strain rate hardening) before plastic strains are generated again. Two simple compressions at fast and slow constant rates are also presented, illustrating the isotach approach used in RASTRA model.

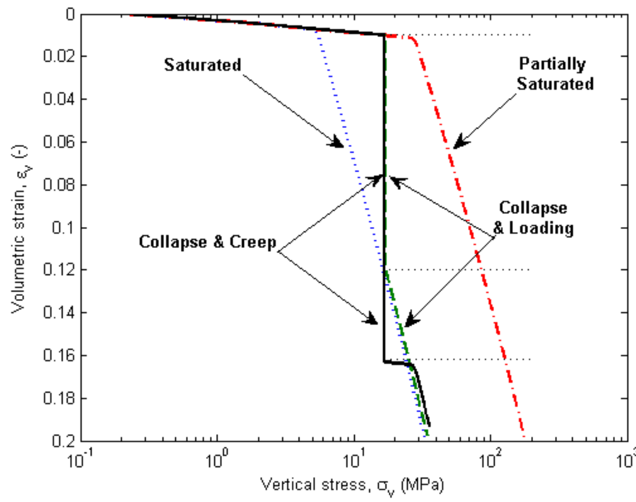

Figure 3: Collapse test followed by creep stage in oedometric cell (solid line).

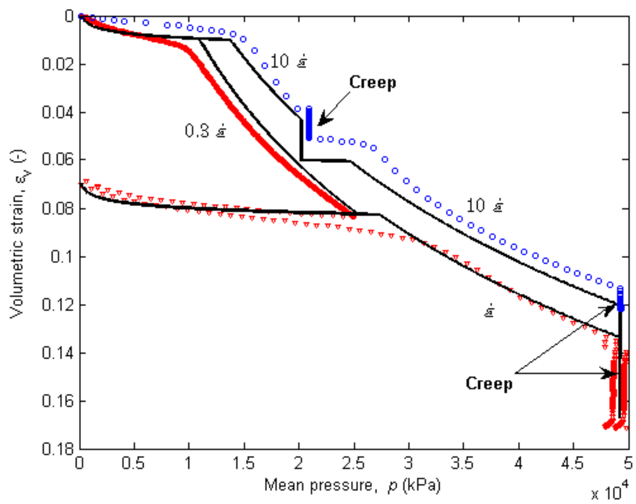

Figure 4: Isotropic compression at various rates, including creep stages, comparison between numerical simulations and experimental data on a reservoir chalk under constant oil-water suction.

Figure 3 shows a collapse test followed by a creep stage under oedometric conditions. The initial compression is performed at a constant suction of 2 MPa. The collapse under constant net stress corresponds to the decrease of the suction value until saturated conditions. Again, the subsequent creep stage is equivalent to a decrease of the strain rate. The test ends up with a further mechanical loading. Three distinct tests are also shown in the figure. The two first are simple compressions at constant suctions of 0 and 2 MPa respectively. The third test is similar to the collapse test but does not include creep phase. This figure illustrates the importance of taking into account time effects since significant irreversible strains may appear after a wetting induced collapse. These strains are due to creep, itself reinforced by low values of suction (see Eqs. (4) and (5)). It should be noted that the three saturated curves after collapse do not exactly coincide. This is due to the coupling between suction and strain rate as introduced in (5).

TABLE I. CONSTITUTIVE PARAMETERS OF RASTRA MODEL.

Parameter		Unit	Value
Elastic swelling (suction)	κ_s	-	10^{-5}
Plastic compressibility (suction)	λ_s	-	10^{-4}
Elastic swelling (mechanical)	κ	-	0.004
Poisson's ratio	ν	-	0.3
Saturated plastic compressibility	$\lambda(0)$	-	0.15
Suction dependent compressibility parameter	r	-	0.90
Suction dependent compressibility parameter	β	MPa^{-1}	0.25
Loading collapse (LC) locus	p_c	MPa	0.01
Suction Increase (SI) locus	s_o	MPa	30.0
Yield stress-strain rate relationship parameter	$\dot{\varepsilon}_v^{ref}$	s^{-1}	7.0
Yield stress-strain rate relationship parameter	p_{ro}^{ref}	MPa	28.0
Yield stress-strain rate relationship parameter	α_0	-	0.108
Yield stress-strain rate relationship parameter	b	MPa^{-1}	0.043

Finally, Figure 4 presents experimental isotropic compressions at various loading rates, including creep stages. It appears that RASTRA is able to reproduce not only qualitatively but also quantitatively the overall behaviour of reservoir chalk under partial saturation.

CONCLUSIONS

An elastoplastic model for partially saturated geomaterials has been presented. Based on the isotach approach, it extends the Barcelona Basic Model for partially saturated materials to take into account rate effects. Numerical simulations have demonstrated the capabilities of the model to quantitatively address fundamental aspects of the rate dependent behaviour of partially saturated geomaterials.

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